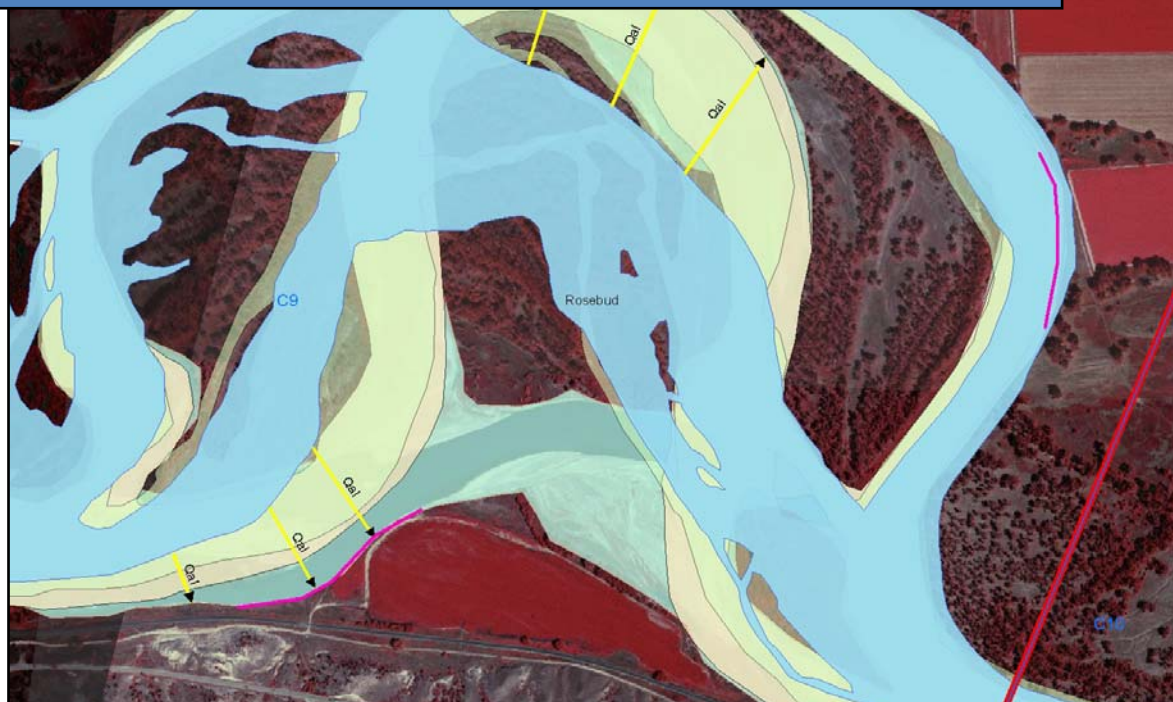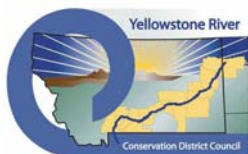# Final Report

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Yellowstone River Channel Migration Zone Mapping

Prepared for:

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1.0 Introduction

This report describes the development of a Channel Migration Zone (CMZ) map for the portion of the Yellowstone River that extends from the Park County/Sweetgrass County line near Springdale, Montana to its confluence with the Missouri River in McKenzie County, North Dakota. This mapping supports the Yellowstone River Conservation District Council in their efforts developing best management practices and performing a cumulative effects assessment of the river corridor.

Channel Migration Zone mapping is based on the understanding that rivers are dynamic and move laterally across their floodplains through time. As such, over a given time period, rivers occupy a corridor area whose width is dependent on rates of channel shift. The processes associated with channel movement include slow channel migration, which is captured in the map by the Channel Migration Zone, and more rapid channel avulsion, which is described by the Avulsion Potential Zone (APZ). These processes and related hazards can be highlighted and presented by using the CMZ mapping techniques.

1.1   Channel Migration

Along the majority of its extent, the Yellowstone River is an *alluvial* river, meaning it flows through sediment that has been deposited by the river itself (versus bedrock, concrete, etc.). As a result, the river is in a constant state of sediment reworking, as it builds point bars, erodes banks, and conveys sediment downstream. Over a given timeframe, the river thereby occupies a *corridor* that extends beyond its current channel boundaries. The width of this corridor is reflective of the rates of lateral shift that are characteristic of a given stream segment. Some stream segments, or *reaches*, migrate relatively slowly due to low stream energy such as low slope, or where the channel flows through resistant boundary materials such as old river terraces or bedrock. Conversely, some segments migrate rapidly where the stream energy and sediment loads are relatively high and the erosion resistance of the channel perimeter is low.

1.2   Channel Avulsion

Numerous reaches of the Yellowstone River have multiple stream channels. Because of this multi-channeled stream pattern, the river corridor hosts a mosaic of active side channels and abandoned floodplain channels that display a range of main channel connectivity. In some areas, split flow through multiple channels occurs at low flow conditions. In other areas, relic abandoned channels are not accessible by low flows and only convey river water during flood events. When minor channels convey water during floods, they are prone to enlargement and reactivation. Sometimes, a small channel can capture the main thread of the river and become the primary channel. This process of rapid channel shift into a new primary channel, called *avulsion*, is different than that of lateral channel migration, and as such poses a different challenge in river management.

1.3   The Channel Migration Zone

The concept of a Channel Migration Zone (CMZ) refers to a river *corridor* that includes areas prone to natural channel occupation due to bank erosion over a given timeframe (Rapp and Abbe, 2003, Skidmore, et al, 1999). The project reach of the Yellowstone River ranges from conditions of highly erodible, dynamic channel margins, to very stable bedrock-controlled segments. The purpose of the CMZ zone delineation is to generate a defined corridor area that reflects these variable rates of natural channel activity.

1.4   The Avulsion Potential Zone

For this study, areas of high risk for avulsions are defined separately from areas at risk of channel migration as the Avulsion Potential Zone (APZ).

1.5   Relative Levels of Risk

Bankline migration and channel avulsion processes both present some level of risk to property within stream corridors. For this study, the migration and avulsion areas were developed independently. Although the statistical risk of each of these hazards has not been determined, their association with specific river process allows some relative comparison of the type and magnitude of risk. In general, the *Channel Migration Zone* delineates areas that have a moderate risk of channel occupation due to channel migration over the next 100 years. Such bank erosion can occur across a wide range of flows. As such, the risk is not just associated with flood events, as channel migration commonly occurs as a relatively steady process. In contrast, *avulsion* tends to be a flood-driven process, and as such, risks identified by the *Avulsion Potential Zone* are typically associated with infrequent, relatively rapid shifts in channel course.

1.6   Potential Applications

The CMZ maps developed for the Yellowstone River identify areas prone to lateral channel shift over the next 100 years. These results are intended to support a myriad of applications. Potential applications for the CMZ maps include the following:

- Assisting in the development of river corridor best management practices;

- Supporting the ongoing cumulative effects assessment by identifying areas isolated from the modern river by features such as bank armor and dikes;

- Improving stakeholder understanding of the geomorphic behavior of this large river system;

- Supporting planning decisions at local and county levels by identifying relative levels of erosion risk;

- Facilitating productive discussion between regulatory, planning, and development interests active within the river corridor; and,

- Supporting other ongoing studies related to the cumulative effects assessment, such as the evaluation of changes in riparian vegetation through time.

1.7　Disclaimer

*The corridor delineations presented in this document are intended to provide a basic screening tool to help guide and support management decisions within the Yellowstone River corridor. The expanse of the project area requires that the results are broad-scale in nature, and therefore less precise than highly detailed site-specific analyses. The results are unequivocally **not** intended to replace or override site-specific assessments; conversely, they are intended to highlight areas that would warrant such assessments as necessary.*

1.8　Acknowledgements

This effort was performed for the Yellowstone River Conservation District Council (YRCDC) through a contract between the Custer County Conservation District and the DTM Consulting/Applied Geomorphology Project Team. Nicole McLain and Carol Watts were instrumental in providing contract management and facilitating communication between the authors and project sponsors. Feedback from the YRCDC and the YRCDC Technical Advisory Committee (TAC) was critical in developing the maps. We especially extend our thanks to YRCDC TAC members Warren Kellogg (NRCS) and Jim Robinson (DNRC), as well as Karl Christians of DNRC for providing insightful review and discussion of the draft submittal. The project team extends its gratitude to all involved parties that facilitated this effort.

2.0 Physical Setting

The following summary of the Yellowstone River corridor geology and geomorphology is intended to provide basic context regarding the physical conditions within the project reach. Because of the large scale of this project (over 400 miles of river), it is important to consider the variability in physical conditions that control river form and process. Much of this information is derived from the report entitled Geomorphic Reconnaissance and GIS Development, Yellowstone River, Montana: Springdale to the Missouri River (AGI and DTM, 2004).

2.1   Regional Geologic History

From Springdale, Montana, to its mouth, the Yellowstone River flows through what is known as the Northern Great Plains physiographic province, a broad surface that slopes eastward from the Rocky Mountain Front towards the Missouri River. Throughout its course, the Yellowstone River is strongly affected by the bedrock geology of the Northern Great Plains, which largely consists of sedimentary rocks that are Cretaceous and Tertiary in age (65 to 150 million years old). These rocks formed when uplift of the Rocky Mountains drove extensive erosion of the growing mountain range, and eastward transport of sediment. This material was then deposited as extensive layers of sand, silt, and organic matter on the gently sloping terrain.

During Pliocene time (over 2.5 million years ago), river systems began to dissect the Northern Great Plains, exposing the accumulated layers of sandstone, shale, and coal. At this time, the ancestral Yellowstone River drained northward to Hudson Bay (Wayne and others, 1991). When continental glaciation began about 2.5 million years ago, ice repeatedly blocked the easterly flowing rivers, causing them to form lakes, spill across divides, and form new courses. At one point, a lobe of the ice sheet extended as far south as Intake, blocking the course of the Yellowstone River (Howard, 1960), and forming Lake Glendive near present-day Glendive. Lake Glendive eventually reached upstream of Miles City to near Hathaway. About 20,000 years ago, the ice sheet retreated to the north, shifting and dropping the river's mouth. This base level lowering caused the river to downcut into its valley fill, resulting in the formation of a series of terraces that bound the river today (Zelt and others, 1999). These terraces are important components of the Channel Migration Zone delineation, as the lowermost terraces commonly form the margin of the river, and are prone to erosion.

2.2 Valley Wall Geology

The Yellowstone River flows through a well-defined river valley that has eroded through sandstone, shale, and coal. The variability in rock types along the river course has resulted in major variations in valley width (AGI and DTM, 2004). Where the valley wall is made of shale, the valley tends to be relatively wide. A plot showing this correlation is shown in Figure 2-1. In this figure, each bar represents a 3-mile length of valley; the Valley Mile (VM) referencing reflects the valley distance upstream from the mouth of the Yellowstone Missouri River confluence. Each 3 mile segment has been attributed by the primary geology at the margin of the river valley. The yellow bars

represent a series of shale units between Billings and Park City (Valley Mile 294-327), where valley is typically over 2.5 miles wide. River at the The Bearpaw shale, depicted as red columns on Figure 2-1, can be correlated to valley floor widening from Huntley to Pompey's Pillar (VM 261-288), in Mission Valley (VM 212-230), and in Hammond Valley (VM 199-206). Towards the river mouth, the Tongue River member of the Fort Union Formation is similarly associated with a relatively wide valley bottom. Whereas shales are typically associated with valley bottom widening, the narrowest valley bottom in the study reach occurs between Springdale and Park City, where the valley walls are comprised of resistant sandstone of the Hell Creek Formation.
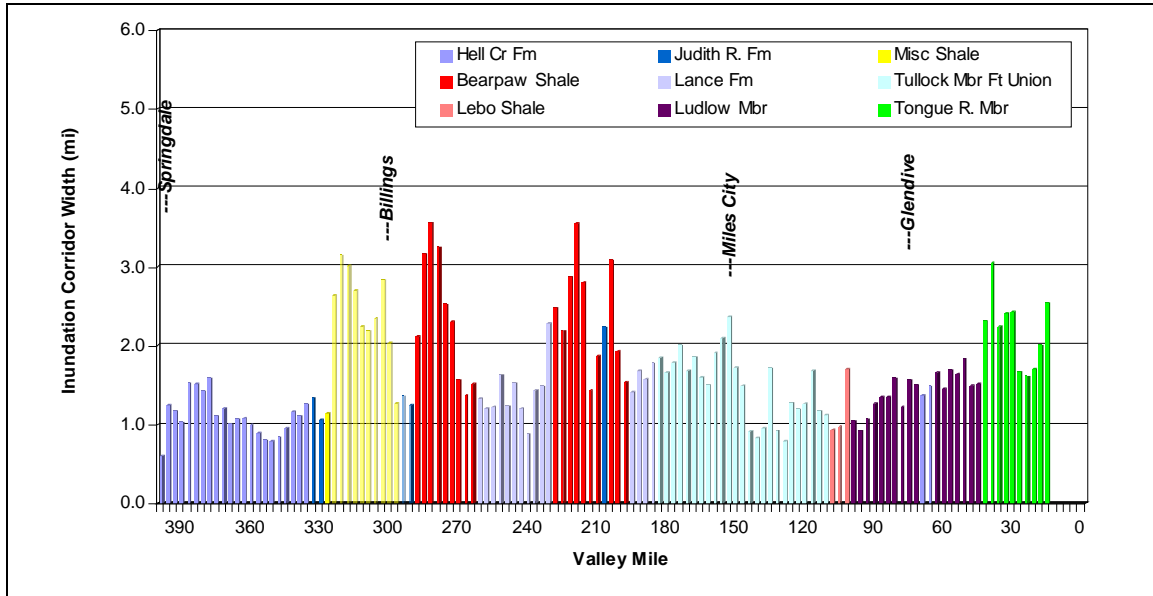
Figure 2-1. Valley bottom width and associated valley wall geology.

2.3   Quaternary Terraces

As described in Section 2.1, the Yellowstone River has eroded the Northern Great Plains landscape over the past few million years. On most river systems, this process of vertical downcutting to form a stream valley is characterized by periods of active incision that are separated by periods of relative stability. During these periods of relative stability, the river migrates laterally, forming a floodplain. When incision resumes, downcutting of the river below its floodplain perches that surface as a terrace. Most river terraces are abandoned floodplain surfaces, which is why they tend to be flat, and draped by stream deposits (Figure 2-2).
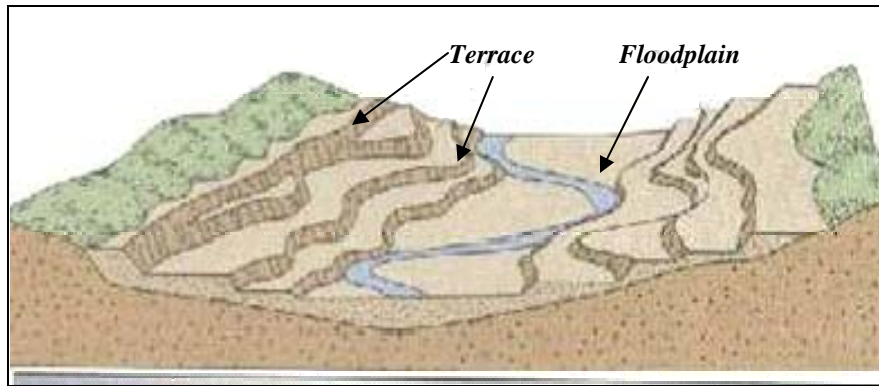
Figure 2-2. Schematic diagram of a typical river valley floodplain and terrace configuration (unt.edu).

Quaternary-age terraces along the Yellowstone River valley extend from the lower river upstream to the Paradise Valley (Figure 2-3). The terraces are typically coarse grained sediments that were deposited during a period of extensive alpine glaciation in the upper watershed (Zelt and others, 1999). Individual terrace surfaces tend to converge in the upstream direction, which reflects the progressive entrenchment of the lower reaches of the river. The same high terrace surface that is approximately 380 feet above the river near Glendive, is only 120 feet above the river near Billings. In the vicinity of Billings, five distinct Pleistocene-age terrace units have been mapped above the elevation of the modern river and its alluvial deposits (Lopez, 2000;Table 2-1).
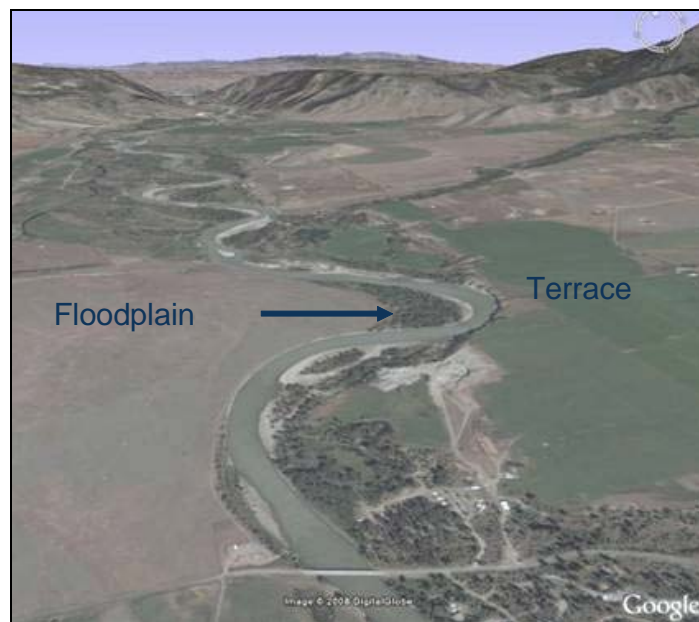
Figure 2-3. River floodplain and terrace downstream of Pine Creek Bridge in the Paradise Valley, Yellowstone River.

Table 2-1. Descriptions of mapped terraces in the vicinity of Billings (Lopez, 2000).

Geologic Map Unit	Thickness (ft)	Estimated height above river (ft)	Reference in Channel Migration Zone
Qat1	20-40	10-20	LT: "Low Terrace"
Qat2	40-60	20-40	HT: "High Terrace"
Qat3	20-30	50-90	None
Qat4	20	200-300	None
Qat5	20	400-500	None

The only two terraces that have been identified as directly influencing the Channel Migration Zone boundaries are the Low Terrace (LT; Qat1) and the High Terrace (HT; Qat2). None of the higher terraces were identified as forming actively eroding margins of the modern river corridor; these high terraces are typically either hundreds of feet away from the river, or characterized by a gravel veneer over bedrock, perched well above the active channel.

2.4 River Morphology

Koch (1977) concluded that in the mid-1970's, the general character of the Yellowstone River main stem was very similar to that observed during the William Clark expedition of 1806. This general characterization consisted of anabranching (abundant side channels) and braided reaches with gravel bars, and intervening reaches with very few islands and minimal gravel bars.

Based on a classification system developed for the project reach, the river has been divided into 67 reaches between Springdale and the Missouri River (AGI and DTM, 2004). These reaches average approximately 7 miles in length, and the classification applied to each reflects conditions such as stream pattern (number of side channels, sinuosity), and confinement (presence of bedrock). Appendix A contains a list of project reaches and their general locations. The classification scheme utilized in the reach assessment is summarized in Appendix B.

Between Springdale and the Yellowstone River/Missouri River confluence, the physiography of the Yellowstone River and its tributaries transitions from steep, confined mountainous areas to plains conditions. As part of the geomorphic reconnaissance study (AGI and DTM, 2004), the corridor was subdivided into four regions (Figure 2-4).

- Region A: From Springdale to the Clarks Fork confluence near Laurel, the river contains a total of 18 reaches. These reaches are typically anabranching (supporting long side channels separated by the main channel by wooded islands), as well as braided (supporting split flow channels around open gravel bars). The reaches are typically "partially confined", indicating that the bedrock valley wall commonly affects one bank of the river. The low terrace commonly follows the channel edge, and a few exposures of high terrace form the modern channel margin.

- Region B: Between the Clarks Fork confluence and the Bighorn River confluence, the river contains 12 reaches. Reach types are variable, ranging from straight to braided. Similar to Region A, bedrock valley wall controls are intermittent. Both low terrace and high terrace features locally form the channel bankline.
- Region C: Between the Bighorn River and the Powder River, Region C consists of a lower gradient system that supports a wide range of reach types. A total of 21 reaches have been identified in Region C, and these reaches range from unconfined, multi-thread channels in the Mission and Hammond Valleys, to highly confined areas downstream of Miles City.
- Region D: Below the Powder River confluence, Region D contains 16 reaches. The uppermost segments of this region, from the Powder River to Fallon, are closely confined by bedrock valley walls. Downstream of Fallon, confinement is reduced, and broad islands are common.
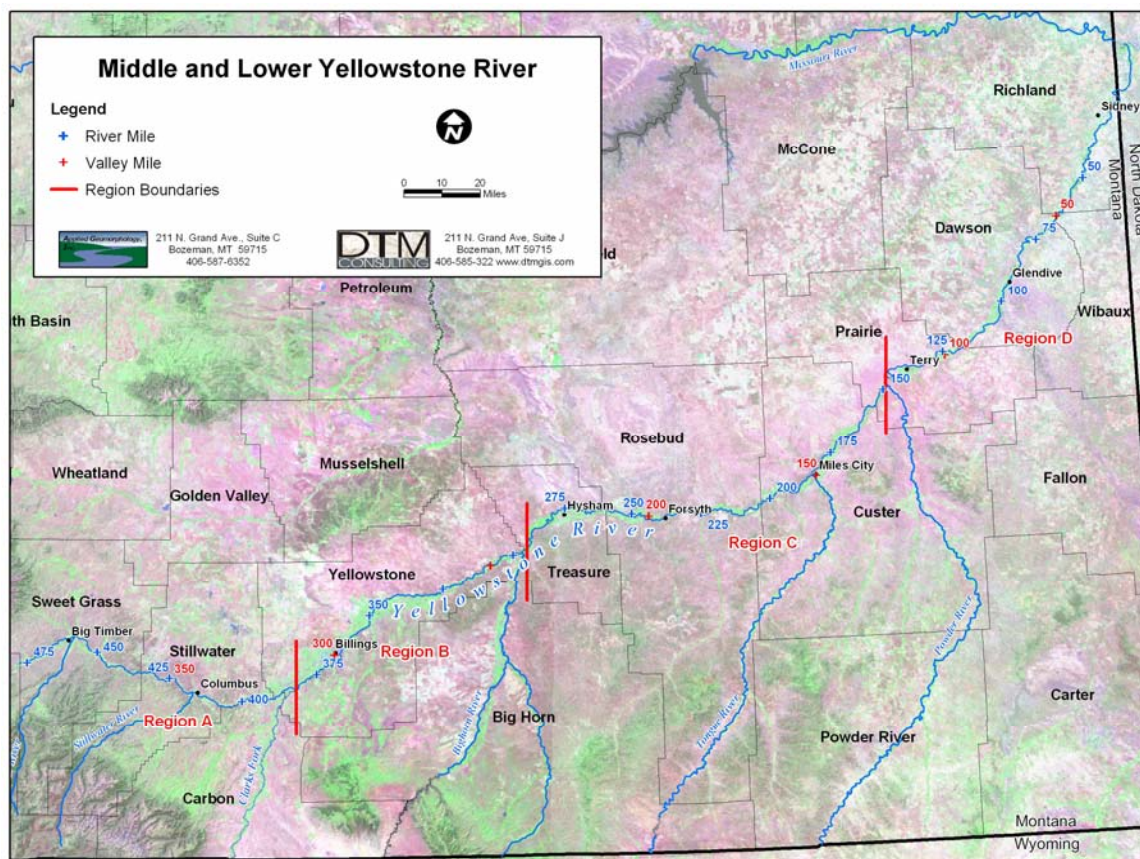

Figure 2-4. Regional geomorphic zones of the Middle and Lower Yellowstone River

3.0 Methods and Results

The methodology applied to the CMZ delineation generally follows the techniques outlined in Rapp and Abbe (2003). The channel migration zone (CMZ) developed for the Yellowstone River is defined as a composite area made up of the existing channel, the historic channel since 1950 (Historic Migration Zone, or HMZ), and an Erosion Buffer that encompasses areas prone to channel erosion over the next 100 years. Areas within this CMZ that have been isolated by constructed features such as armor or floodplain dikes are attributed as "Restricted Migration Area" (RMA). Beyond the CMZ boundaries, outlying areas that pose risks of channel avulsion are identified as "Avulsion Potential Zones".

Channel Migration Zone (CMZ) = Historic Migration Zone (HMZ) + Erosion Buffer

Restricted Migration Area (RMA) = Areas of CMZ isolated from the current river channel by constructed bank and floodplain protection features

The following sections describe the methodologies for developing the individual components of the CMZ maps. These methodologies are adapted from those presented in Rapp and Abbe (2003) to accommodate the scale of the project area, available data sources, and the anticipated level of effort required.

3.1   The Historic Migration Zone (HMZ)

The Historic Migration Zone is based on a composite area defined by the channel locations in 1949-1951, 1976, 1995, and 2001 (Figure 3-1). The resulting area reflects the zone of channel occupation over a 50-year timeframe. The method for delineating the HMZ is to overlay the digitized polygons for the bankfull channel for each time series, and merge those polygons into a single HMZ polygon. The bankfull channel reflects the active channel area that is comprised of unvegetated substrate, and its boundaries are delineated as the boundary between open channel and woody vegetation stands, terrace margins, or bedrock valley wall. The HMZ contains all unvegetated channel threads that are interpreted to convey water under bankfull conditions (typical spring runoff), and as such, the zone has split flow segments and islands. All islands within the HMZ are included with the merged HMZ polygon.
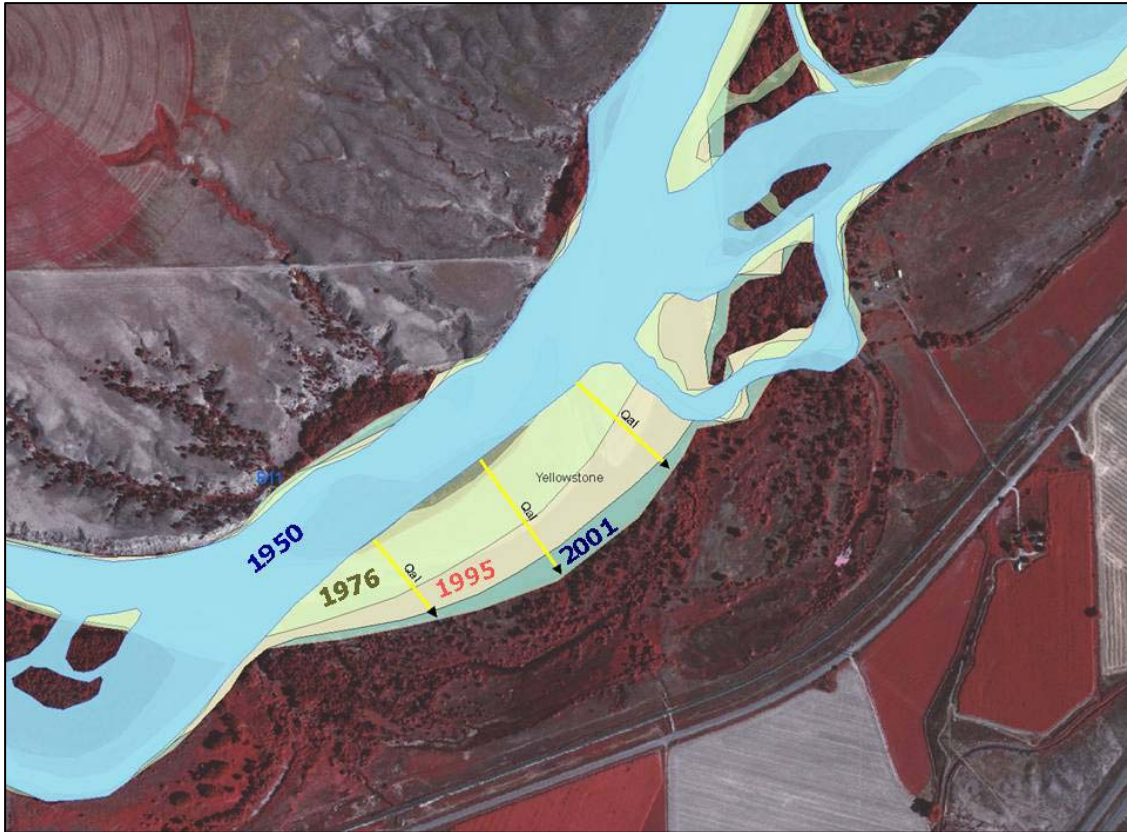
Figure 3-1. Composite Historic Migration Zone (HMZ) showing bendway migration from 1950-2001; migration lines are shown as arrows.

3.2 The Erosion Buffer

To address anticipated future migration beyond the historic corridor boundary, an Erosion Buffer has been developed and added to the 2001 channel margin. This area is considered prone to channel occupation over the life of the CMZ (100 years), and is based on mean migration rates for a given channel segment, or reach. To determine the buffer distance, migration rates from 1950 to 2001 were measured throughout the corridor. The rates were then used to calculate the anticipated migration distances for a 100-year timeframe. This approach to determining the Erosion Buffer is similar to that used in Park County (Dalby, 2006), on the Tolt River and Raging River in King County, Washington (FEMA, 1999), and as part of the Forestry Practices of Washington State (Washington DNR, 2004). Over 1200 individual measurements of channel migration were made and recorded in the project GIS. For each migration site, three measurements were collected, and the average of those three measurements was calculated to represent the migration distance and rate at the site. An example of a single bendway migration site measurement is shown as three migration lines in Figure 3-1. A reach with multiple sites is shown in Figure 3-2.
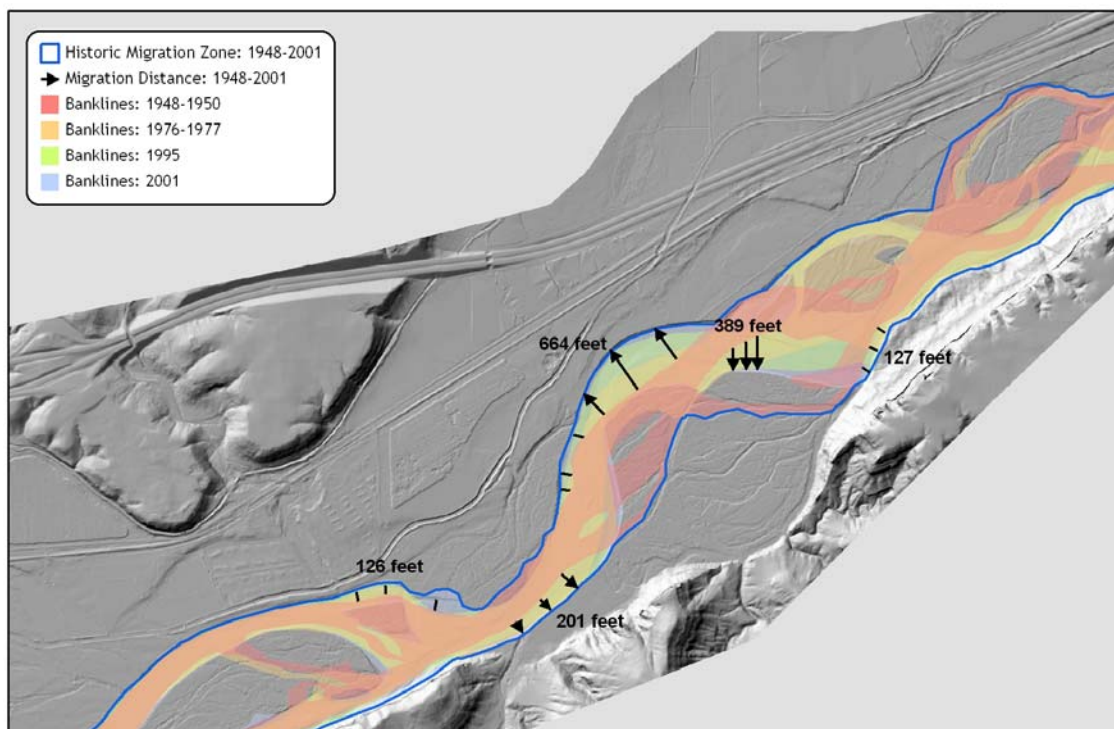
Figure 3-2. Migration distance measurements.

3.2.1 Geologic Controls on Migration Rate

Any given area that the Yellowstone River has eroded over the past 50 years may consist of alluvium, terrace, or bedrock materials. For this study, very little migration was measureable into the bedrock valley walls, hence these units were excluded from the analysis. The Low Terrace (LT) and High Terrace (HT), however, show some cases of active erosion by the river. In order to effectively assess the potential for channel migration into these units, they were mapped in the GIS, and then any migration lines that extended into these units were attributed as such. The data for these sites, which reflect channel migration into terraces, was then summarized as an independent dataset.

The geologic mapping of terraces on the river margin relied on existing geologic maps, air photos, and, where available, LIDAR imagery. This mapping effort was challenging due to the variable heights and expression of these surfaces on the air photos. Where LIDAR imagery is available (Stillwater, Yellowstone, and Dawson Counties), delineation of terraces was fairly straightforward due to the detailed topographic mapping. In other counties, geologic maps and 2001 color-infrared photographs were used to define the map units. Several areas were field checked to correlate mapping results to ground conditions. In general, combined evidence related to vegetation patterns, land use, and existing mapping appear to provide a good foundation for mapping terraces. However, not all areas were field checked, and some surfaces are likely inappropriately identified. Areas where riparian areas have been cleared and farmed, or where the low terrace is only a few feet higher than the floodplain are most prone to being mis-mapped. It is

therefore critical to note that these maps are intended to provide a best-effort screening tool, and that field observations can be used to refine buffer widths if necessary. Also, the future acquisition of LIDAR imagery for the remaining river corridor will likely be helpful in further distinguishing low terrace areas from younger alluvium.

The units mapped in the GIS include HT (High Terrace), LT (Low Terrace) AL (alluvium), and B (Bedrock). A schematic cross section showing the configuration of alluvium, terraces, and bedrock is shown in Figure 3-3. Bedrock (B) intermittently forms bluffs along the river's edge, and these bluffs are typically taller than the high terrace (HT). The most common material bounding the river channel is alluvium (AL), which is that material deposited and frequently reworked by the river. This alluvium, or floodplain, supports the Yellowstone River riparian corridor. Where the river migrates beyond the edge of the alluvium, it reaches the low terrace (LT), which typically forms cutbanks that are 10-20 feet in height. This surface supports extensive agriculture in the corridor, and the railroad commonly follows its edge where it is in contact with the lower elevation floodplain. Locally, the river has eroded laterally to the edge of the high terrace (HT), which forms cutbanks that are over 20 feet tall.
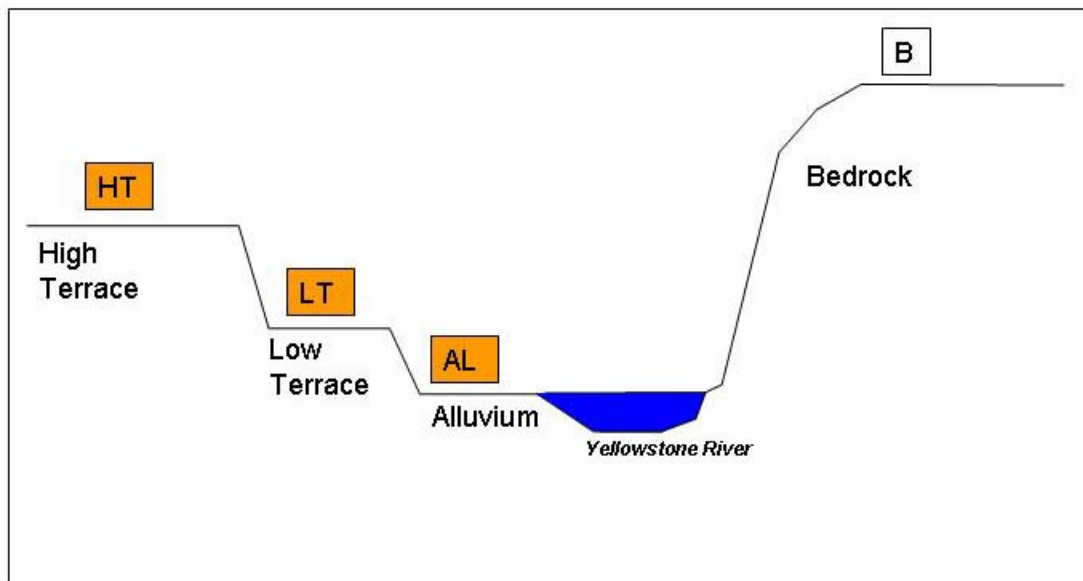
Figure 3-3. Schematic Cross Section showing geologic units addressed in CMZ development.

3.2.2 Migration Rate Statistics

The measured migration distances were statistically summarized by reach. Appendix A contains a list of project reaches and their general locations, and a summary of the classification types is included in Appendix B. Appendix C contains box and whisker plots showing the range of measurements for each reach, and a list of resulting erosion buffers applied to the 2001 bankline is contained within Appendix D.

Because measured migration rates have been stratified in terms of the types of materials eroded, the erosion buffer distance varies within a given reach depending on the materials

that form or are anticipated to form the channel boundary (Table 3-1). Where the river is against modern alluvium, the 100-year erosion buffer was applied. For the lowest two terraces mapped in the river corridor (LT and HT), a 50-year migration time frame was applied to the terraces for the following reasons:

- the terrace features are highly variable in terms of their geotechnical parameters and associated erosion-resistance;
- there were relatively few locations where measurable channel migration through a terrace was observed, resulting in low *n* values in a given reach; and,
- observations of migration patterns indicate that it is unlikely that the river will continually migrate through a terrace feature for the life of the CMZ.

It is therefore important to note that the erosion buffer applied to the terraces is conservative, to prevent an overestimation of the buffer width where terraces are resistant to erosion. For the high (HT) terraces, a geotechnical setback was added to the erosion buffer to accommodate a minimum 3:1 bank angle from the existing channel margin. Based on literature summaries and field observations, this geotechnical setback assumed an average HT bank height of 25 feet. The erosion buffers for terraces were applied on a regional, rather than reach scale. That is, the same buffer distance was applied for the LT in all of Region A, which extends from Springdale to the Clark Fork confluence.

The resulting erosion buffers applied to each reach are shown in Figure 3-4. The values shown are in meters, and reach-specific values reflect measured migration rates through alluvium. The buffer value, which is for a 100-year timeframe, reflects twice the mean 50-yr migration rate distance shown in Appendix B. Single values were developed for the LT and HT terrace values for each region (A, B, C, and D). The high terrace (HT) was not identified as present within the CMZ boundaries of either Region C or Region D.
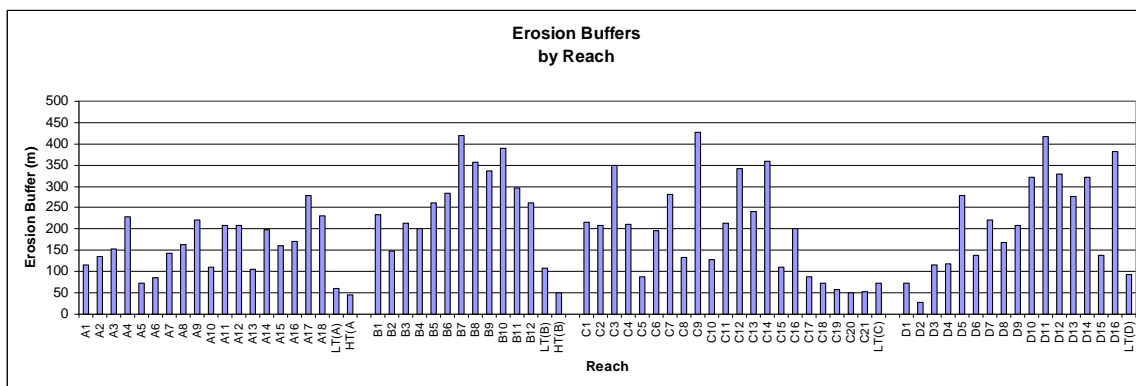
Figure 3-4. Erosion buffers applied to 2001 channel margin, Yellowstone River project reach.

Where the river abuts older terraces, and migration into that terrace is of concern, it would be prudent to perform a more site-specific assessment to define the geotechnical character and associated erodibility of that deposit. A reconnaissance level field assessment was performed to help define the average geotechnical characteristics of the geologic units that comprise the margins of the Yellowstone River corridor, however a

complete field assessment of terrace extents and erodibility was beyond the scope of this project.

An example of the erosion buffer added to the 2001 channel margins is shown in Figure 3-5. Typically, the buffer applied to the AL deposits (recent river alluvium) is greater than that applied to either the low or high terrace (LT or HT, respectively). Where the channel abuts older bedrock units, no buffer was applied. Although these units may be prone to gradual erosion or perhaps mass failure, these processes are site specific and beyond the scope of this project. As such, it is critical to note that hazards likely exist where the river abuts geologic units older than Quaternary-age alluvium and terraces, but that these hazards should be addressed site-specifically. A summary of buffer determination methods is contained in Table 3-1.

Figure 3-5. Erosion buffers applied to 2001 channel margin.

Table 3-1. Summary of methods for determining erosion Buffer for different geologic units.

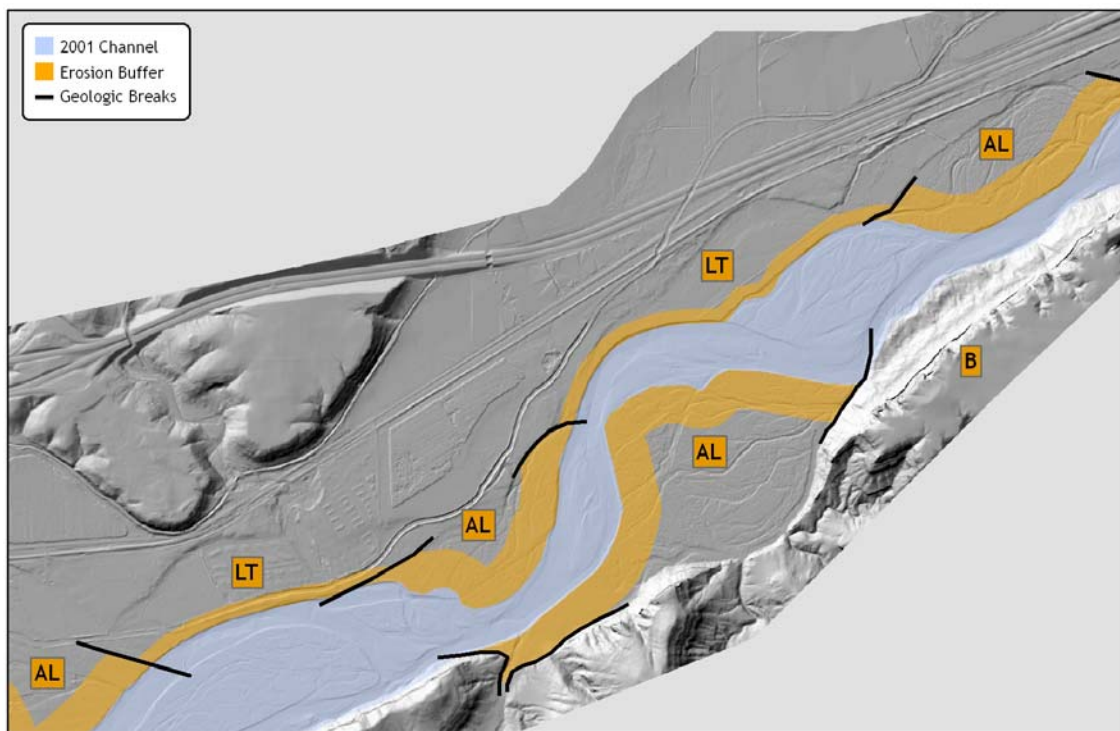| Unit	Erosion Buffer determination method	Comments
AL (Qal)	Measure migration distances from 1950-2001 and calculate average 100 year buffer for each reach.	Allows for progressive migration of river channel across active floodplain area.
LT (Qat1)	Measure migration distances from 1950-2001 and calculate average 50 year buffer for each region.	A 50-year buffer was used to reflect areas prone to erosion against the low terrace. The estimated height of the Qat1 terrace above the river is 10-20 ft (Lopez, 2000).
HT (Qat2)	Measure migration distances from 1950-2001 and calculate average 50 year buffer for each region. Add geotechnical setback for 3:1 slope.	A 50-year buffer was used to reflect areas prone to erosion risk against the high terrace. The estimated height of the Qat2 terrace above the river is 20-40 ft (Lopez, 2000).
Older Geologic Units	None	Site specific geotechnical attributes required.

A summary of calculated erosion buffer widths by reach type shows that the confined channel types (CM and CS) have the smallest erosion buffers, which means the lowest measured rates of migration (Figure 3-6). The partially confined straight reaches (PCS) typically represent a straight channel that is flowing against a bedrock valley wall, also show low rates of channel shift. In contrast, braided, meandering, and anabranching channels all have much higher rates of migration and associated buffer widths. These data suggest that relatively high rates of lateral migration on the Yellowstone River occurs in numerous reach types, and that no single reach type is especially prone to rapid lateral shift.
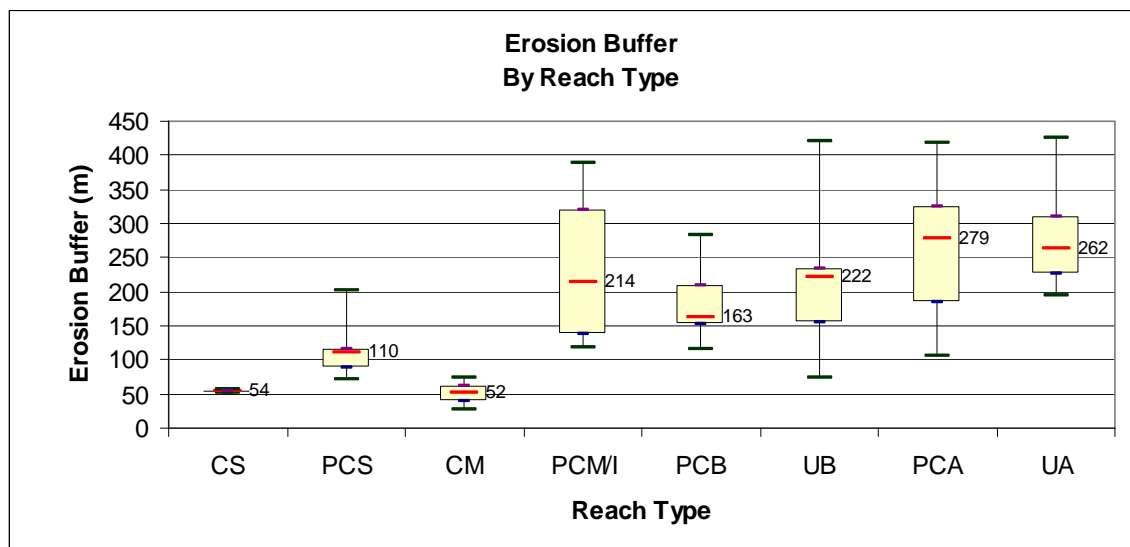

Figure 3-6. Statistical summary of erosion buffer widths by each reach type; labeled values are medians.

3.3   The Restricted Migration Area

In an effort to control lateral erosion of the Yellowstone River, bank protection has been placed in areas of concern. The extent of bank armor within each reach ranges from 0% to almost 50% of the bank length (AGI and DTM, 2004). The effect of this armor is to restrict natural patterns of channel migration. As such, areas within the CMZ may not be wholly accessible to the river due to the erosion resistance of the armored bank. The Restricted Migration Area refers to areas within the CMZ that have been isolated by man-made structures. These features may include bank armor, dikes, embankments, levees, or bridge abutments. The Restricted Migration Areas are identified on the accompanying CMZ maps, and it is intended that in the future, a detailed, quantitative assessment of restricted area will support the Yellowstone River Corridor cumulative effects assessment.

A preliminary summary of the GIS data indicate that the channel types that tend to contain the most islands (anabranching: PCA and UA, and meandering with islands: PCM/I), collectively have the largest extent of CMZ acreage in the project reach (Figure 3-7). However, the braided channel types, which are characterized by extensive split flow around open gravel bars, have the greatest proportion of migration area that is restricted by bank armor and levees (Figure 3-8). These data represent a summation of all acreage within a given reach type. It is also instructive to assess the range of results calculated for each individual reach. A box and whisker plot of the data shows the minimum, 25th percentile, median (labeled), 75th percentile, and maximum for the dataset represented by each reach type (Figure 3-9). For most reach types, there is at least one reach that has over 20 percent of the migration zone restricted by armor, levees, or dikes. The Partially Confined Straight (PCS) reach that is over 20% restricted is located immediately above Huntley Diversion dam (Reach B4); this may exemplify the relationship between infrastructure and CMZ isolation by riprap.
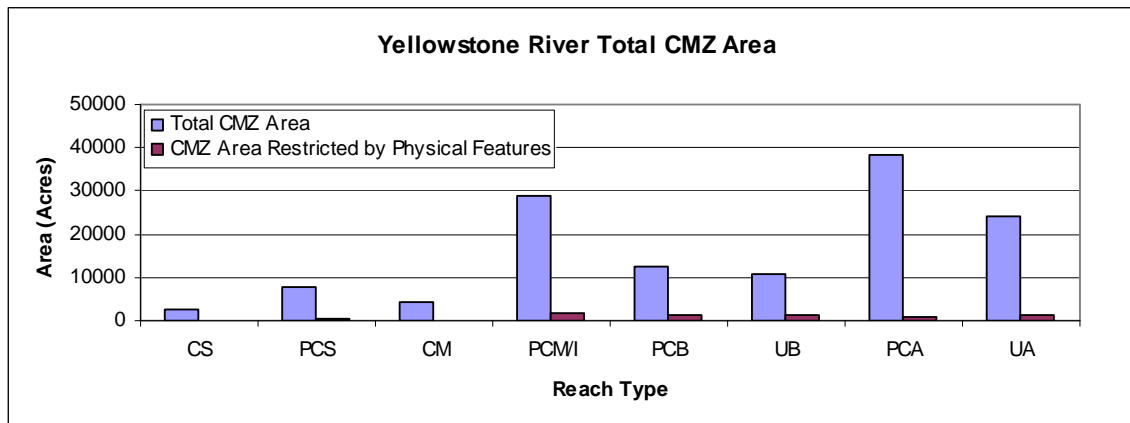
Figure 3-7. **Total channel migration zone area by Reach Type.**
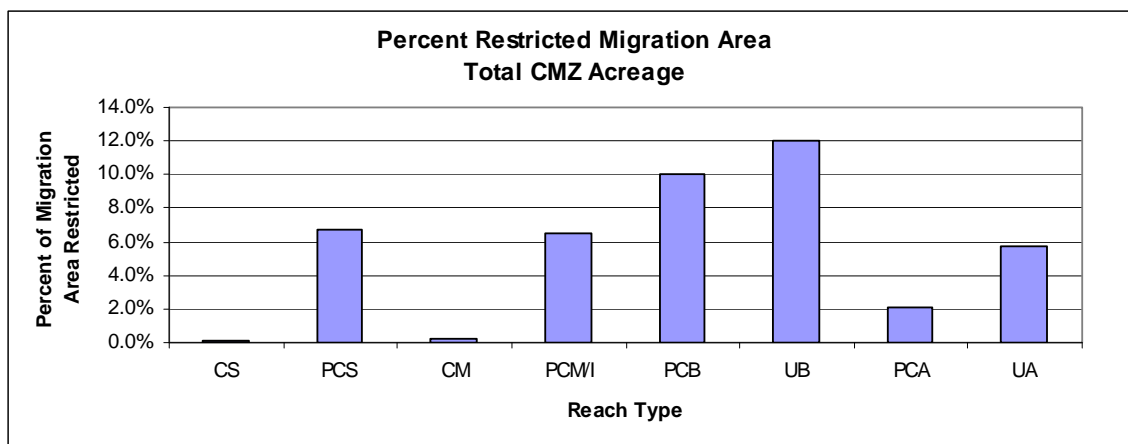
Figure 3-8. Percent of restricted migration area by reach type (total of all acreage).
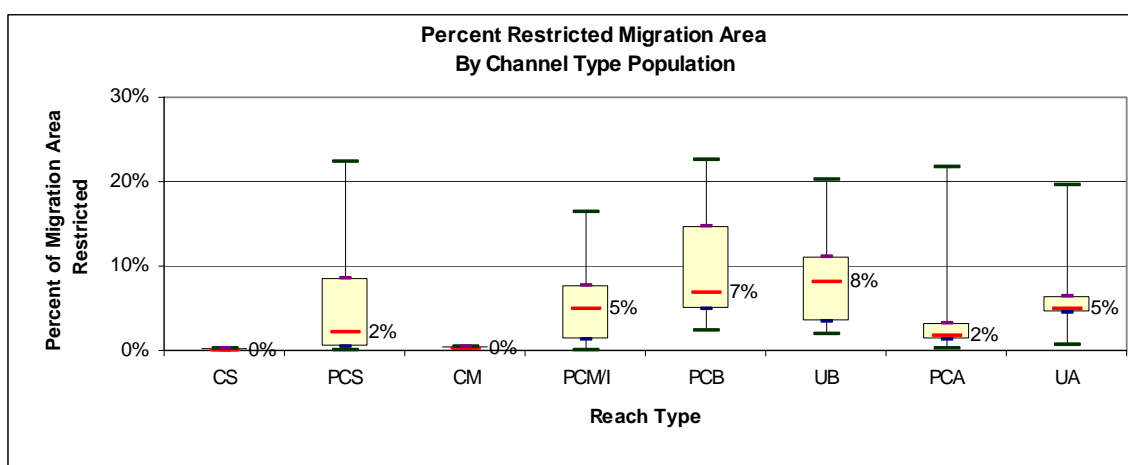
Figure 3-9. Statistical summary of percent restricted migration area by reach type; based on individual reach data (median values are labeled).

3.4   The Avulsion Potential Zone

In many places, the Yellowstone River migrates laterally across its floodplain as a distinct, persistent channel course. However, mapping of historic channel movement on the Yellowstone River indicates that there are places where the river has historically "jumped" channels, or avulsed, due to a range of processes including natural erosion, flood events, and ice jamming. This process, which may be natural or driven by human activities in the stream corridor, creates additional risk of erosion within the river corridor. To address this risk, an avulsion potential zone (APZ) has been developed for the Yellowstone River corridor.

The Avulsion Potential Zone is based on digitized channel courses that are evident beyond the boundaries of the CMZ. It includes areas where discernable floodplain channel remnants are within the active valley bottom; and additionally, areas where bendways are geomorphically mature and appear prone to cutoff. The methodology for determining the APZ is to digitize channel remnants and bendways that are prone to

cutoff, and highlight those areas beyond the CMZ where these features exist (Figure 3-10).
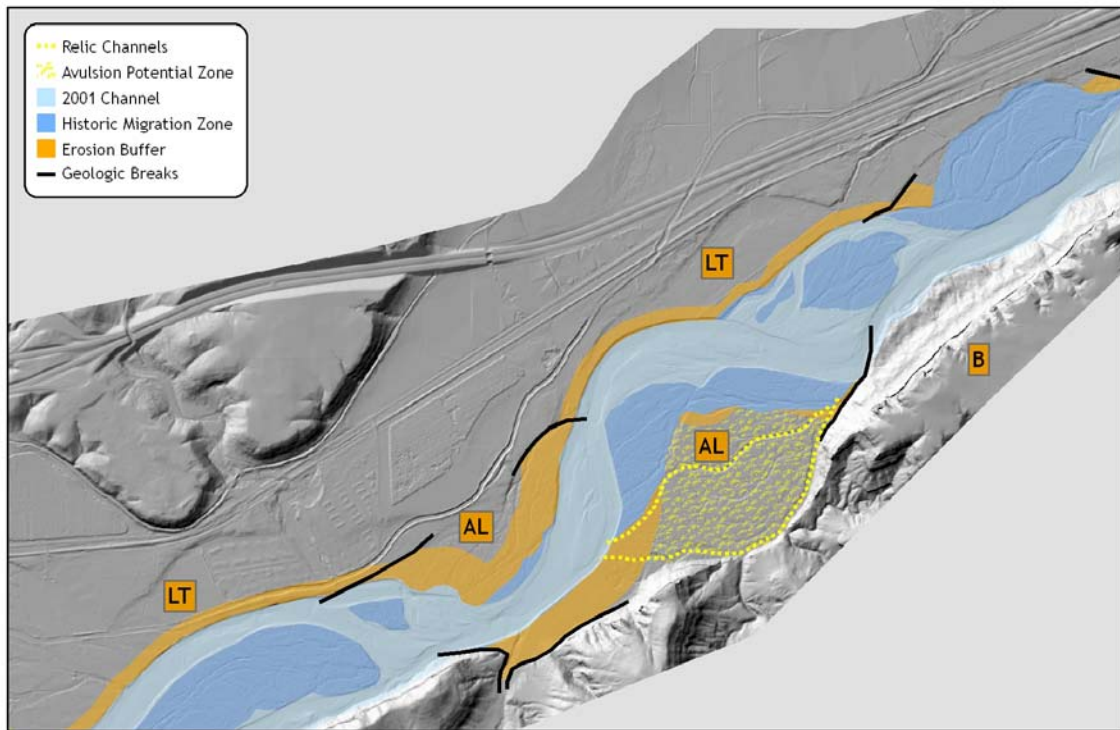
Figure 3-10. CMZ showing digitized floodplain channels (yellow) defining outer margin of the Avulsion Potential Zone.

3.5   Composite Map

Examples of the composite CMZ maps for the Yellowstone River are shown in Figure 3-11 and Figure 3-12. Where LIDAR data exist (Stillwater, Yellowstone, and Dawson Counties), the results can be shown on shaded relief maps (Figure 3-11). For consistency, however, as well as to help users navigate throughout he maps, the 2005 NAIP imagery has been adopted for the base mapping (Figure 3-12). The accompanying deliverable maps for the project reach are presented by county and included on the project CD as PDF files.
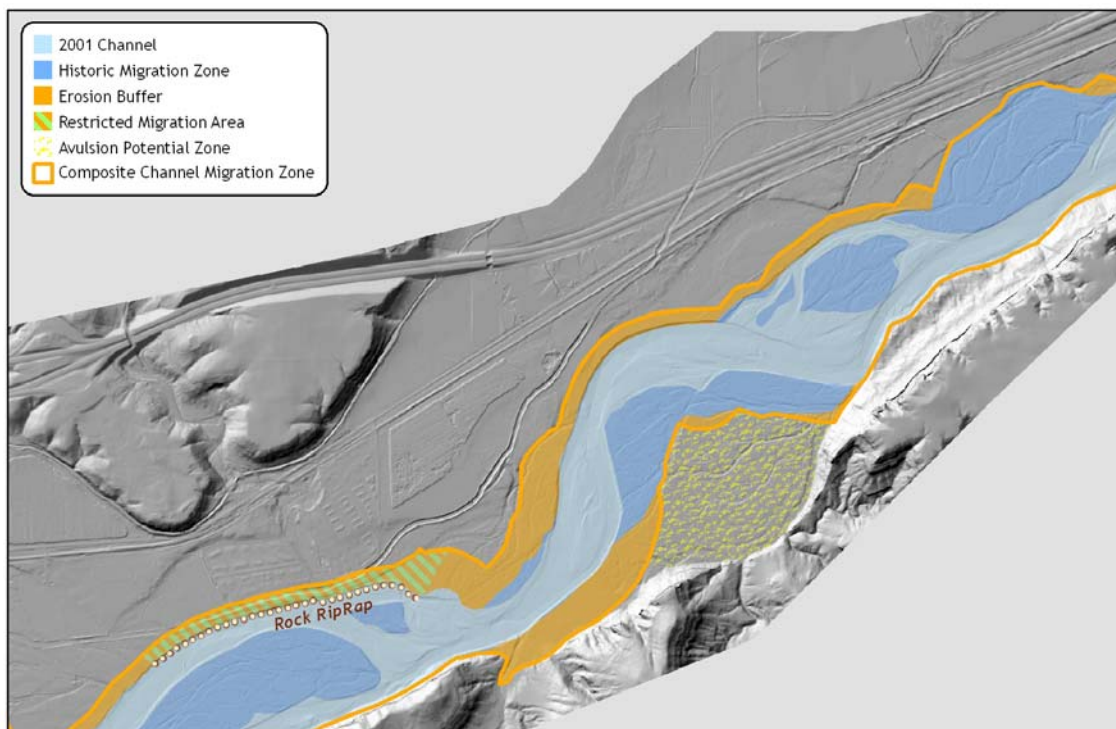
Figure 3-11. Composite Channel Migration Zone on LIDAR base map.
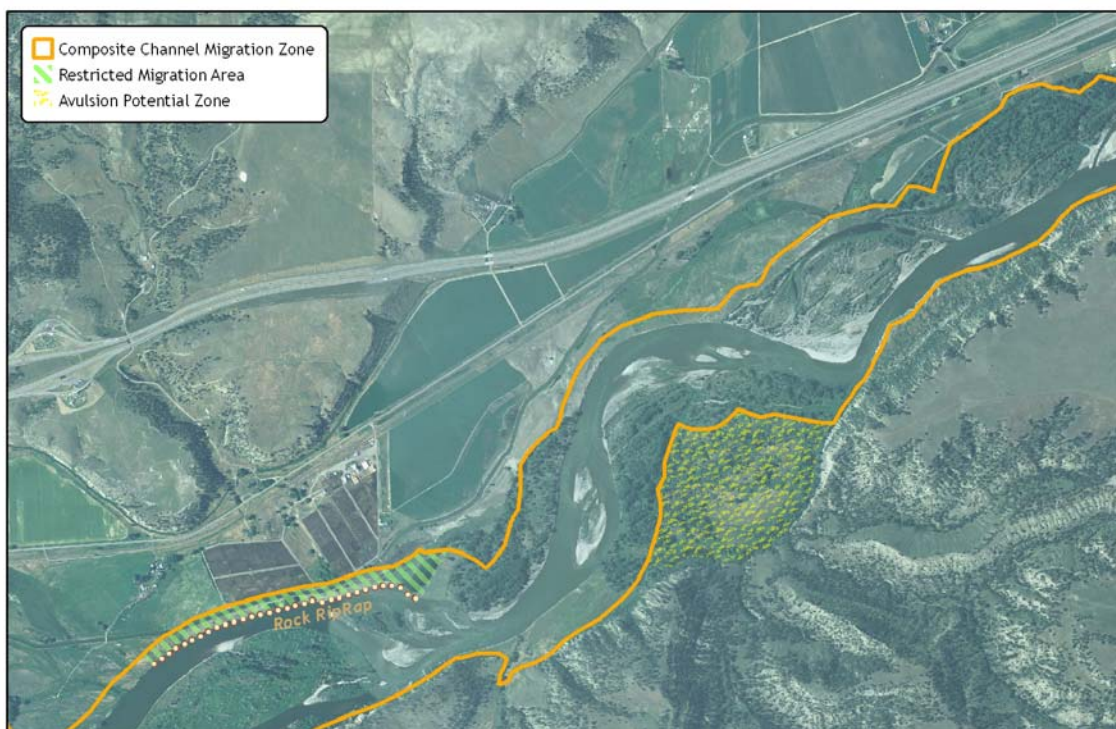
Figure 3-12. Composite Channel Migration Zone on 2005 NAIP imagery.

3.6 Deliverables

The products for this effort consist of a project data CD and a series of county-level maps that delineate the Channel Migration Zone for the Yellowstone River from Sweetgrass County to the Missouri River. The Channel Migration Zone mapping is integrated with results of the Inundation Zone Modeling to provide a composite map showing hazards along the Yellowstone River stemming both from erosion and floodwater inundation.

All new project data are supplied on CD in an ESRI Personal Geodatabase, along with PDF versions of the county-level maps. Each Feature Class is accompanied by appropriate FGDC compliant metadata. All data are in Montana State Plane NAD83 coordinates, in meters.

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Appendix A. Reach Lengths, Classification, and General Location

Table A-1. Summary of reach types and geographic location				
Reach Identification	Length (km)	County	Classification	Comments
A1	5.4	Sweetgrass	PCB: Partially confined braided	*Springdale*: Low primary sinuosity; large open bar area; extensive armoring
A2	11.1	Sweetgrass	UB: Unconfined braided	*Grey Bear* fishing access
A3	8.6	Sweetgrass	PCB: Partially confined braided	Upstream of *Big Timber*; Hell Creek Formation valley wall
A4	5.6	Sweetgrass	UB: Unconfined braided	To *Boulder River* confluence; encroachment at Big Timber; extensive armor
A5	5.2	Sweetgrass	UB: Unconfined braided	Low Qat1 terrace on right bank
A6	4.8	Sweetgrass	PCS: Partially confined straight	Channel closely follows left valley wall
A7	15.9	Sweetgrass	PCB: Partially confined braided	*Greycliff*: Narrow valley bottom with alluvial fan margins
A8	8.2	Sweetgrass	PCB: Partially confined braided	Floodplain isolation behind interstate and R/R
A9	6.2	Sweetgrass Stillwater	UA: Unconfined anabranching	To *Reed Pt*; extensive secondary channels in corridor
A10	6.9	Stillwater	PCS: Partially confined straight	Channel closely follows left valley wall
A11	11.2	Stillwater	PCB: Partially confined braided	High right bank terrace with bedrock toe; *I-90 bridge* crossing
A12	9.8	Stillwater	PCB: Partially confined braided	To *Stillwater* confluence
A13	5.8	Stillwater	PCA: Partially confined anabranching	*Columbus*; extensive armoring, broad islands
A14	12.5	Stillwater	PCA: Partially confined anabranching	Valley bottom crossover
A15	9.5	Stillwater, Carbon	PCB: Partially confined braided	Follows Stillwater/Carbon County line
A16	12.4	Stillwater, Carbon	PCA: Partially confined anabranching	*Park City*: Major shift in land use, and increase in valley bottom width
A17	10.4	Yellowstone Carbon	UA: Unconfined anabranching	To *Laurel;* WAI Reach A
A18	3.8	Yellowstone	UA: Unconfined anabranching	To Clark Fork; land use change to row crops; WAI Reach A
B1	24.6	Yellowstone	UB: Unconfined braided	Extensive armoring *u/s Billings*; WAI Reaches B,C,D
B2	9.8	Yellowstone	PCB: Partially confined braided	*Billings*; WAI Reach E

Table A-1. Summary of reach types and geographic location

Reach Identification	Length (km)	County	Classification	Comments
B3	7.0	Yellowstone	UB: Unconfined braided	Wide corridor d/s *Billings*; WAI Reach F
B4	6.1	Yellowstone	PCS: Partially confined straight	Channel closely follows right valley wall; extensive bank armor
B5	12.0	Yellowstone	UA: Unconfined anabranching	*Huntley:* includes *Spraklin Island*
B6	9.9	Yellowstone	PCB: Partially confined braided	Channel closely follows left valley wall
B7	13.9	Yellowstone	UB: Unconfined braided	Unconfined reach
B8	14.7	Yellowstone	PCA: Partially confined anabranching	*Pompey's Pillar*
B9	7.5	Yellowstone	UA: Unconfined anabranching	Meander cutoff isolated by railroad
B10	11.6	Yellowstone	PCM: Partially confined meandering	Encroached
B11	13.1	Yellowstone	PCA: Partially confined anabranching	To *Custer Bridge*
B12	7.3	Yellowstone	UA: Unconfined anabranching	To *Bighorn River* confluence
C1	9.5	Treasure	UA: Unconfined anabranching	From *Bighorn* confluence: Includes 1 mile of left bank valley wall control; Extensive bank protection.
C2	8.9	Treasure	PCB: Partially confined braided	To *Myers Br* (RM 285.5); Railroad adjacent to channel on valley wall; low sinuosity
C3	7.6	Treasure	UA: Unconfined anabranching	To *Yellowstone Diversion*: very sinuous; large meanders, extensive bars; historic avulsion
C4	6.1	Treasure	PCB: Partially confined braided	Below *Yellowstone Diversion*
C5	5.1	Treasure	PCS: Partially confined straight	*Hysham*
C6	9.1	Treasure	UA: Unconfined anabranching	*Mission Valley*
C7	14.7	Treasure	UA: Unconfined anabranching	*Mission Valley*
C8	10.4	Treasure Rosebud	PCS: Partially confined straight	Rosebud/Treasure County Line
C9	17.2	Rosebud	UA: Unconfined anabranching	*Hammond Valley*
C10	11.0	Rosebud	PCM: Partially confined meandering	*Forsyth*
C11	18.3	Rosebud	PCM/I: Partially confined meandering/islands	To *Cartersville Bridge*
C12	16.2	Rosebud	PCM/I: Partially confined meandering/islands	*Rosebud*; numerous meander cutoffs
C13	10.8	Rosebud	PCM/I: Partially confined meandering/islands	Valley bottom crossover
C14	19.6	Rosebud Custer	PCM/I: Partially confined meandering/islands	Series of meander bends

Table A-1. Summary of reach types and geographic location

Reach Identification	Length (km)	County	Classification	Comments
C15	6.0	Custer	PCS: Partially confined straight	Very low riparian vegetation
C16	11.6	Custer	PCM/I: Partially confined meandering/islands	to *Miles City*
C17	7.2	Custer	PCS: Partially confined straight	*Miles City; Tongue River*
C18	5.2	Custer	PCS: Partially confined straight	Channel follows left valley wall
C19	17.9	Custer	CS: Confined straight	Confined
C20	12.2	Custer Prairie	CS: Confined straight	Confined
C21	15.2	Custer Prairie	CM: Confined meandering	To *Powder River;* confined
D1	19.5	Prairie	CM: Confined meandering	To *Terry Bridge*; confined
D2	17.0	Prairie	CM: Confined meandering	To *Fallon, I-90 Bridge*; confined
D3	13.4	Prairie Dawson	PCS: Partially confined straight	Hugs right bank wall; into Dawson County
D4	17.7	Dawson	PCM/I: Partially confined meandering/islands	
D5	20.3	Dawson	PCA: Partially confined anabranching	Long secondary channels; to *Glendive*
D6	8.9	Dawson	PCM/I: Partially confined meandering/islands	*Glendive*
D7	12.3	Dawson	PCA: Partially confined anabranching	
D8	16.4	Dawson	PCA: Partially confined anabranching	To *Intake*
D9	5.6	Dawson	PCM/I: Partially confined meandering/islands	Downstream of *Intake*
D10	18.3	Dawson Wibaux Richland	PCA: Partially confined anabranching	Vegetated islands
D11	10.3	Richland	PCA: Partially confined anabranching	*Elk Island:* Very wide riparian; marked change in channel course since 1981 geologic map base
D12	21.9	Richland	PCA: Partially confined anabranching	Secondary channel on valley wall; Sinuous; long abandoned secondary channel
D13	13.8	Richland	PCM/I: Partially confined meandering/islands	
D14	23.1	Richland, McKenzie	PCM/I: Partially confined meandering/islands	Into *McKenzie County, North Dakota*: High sinuosity
D15	9.6	McKenzie	PCM/I: Partially confined meandering/islands	
D16	11.9	McKenzie	US/I: Unconfined straight/islands	*To mouth*: low sinuosity; alternate bars; vegetated islands

Appendix B.   Channel Classification Scheme

Table B-2. Channel classification

Type Abbrev.	Classification	n	Slope (ft/ft)	Planform/ Sinuosity	Major Elements of Channel Form
UA	Unconfined anabranching	12	<.0022	Mult. Channels	Primary thread with vegetated islands that typically exceed 3X average channel width
PCA	Partially confined anabranching	18	<.0023	Mult. Channels	Partial bedrock control; Primary thread with vegetated islands that exceed 3X average channel width
UB	Unconfined braided	6	<.0024	Mult. Channels	Primary thread with unvegetated gravel bars; Average braiding parameter generally >2 for entire reach
PCB	Partially confined braided	13	<.0022	Mult. Channels	Partial bedrock control; primary thread with gravel bars; Average braiding parameter generally >2
PCM	Partially confined meandering	4	<.0014	>1.2	Partial bedrock control; main channel thread with point bars; average braiding parameter <2
PCS	Partially confined straight	11	<.0020	<1.3	Partial bedrock control; low sinuosity channel along valley wall
PCM/I	Partially confined meandering/islands	11	<.0007	Mult. Channels	Partial bedrock control; sinuous main thread with stable, vegetated bars
CS	Confined straight	5	<.0001	<1.2	Bedrock confinement; low sinuosity
CM	Confined meandering	7	<.0008	<1.5	Bedrock confinement; sinuous; uniform width; small point bars
US/I	Unconfined straight/islands	1	<.0003	<1.2	Low sinuosity with vegetated bars

Appendix C. Channel Migration Measurement Results

Figure C-1. Statistical results for migration distances measured for Region A (Springdale to Clark Fork River Confluence)
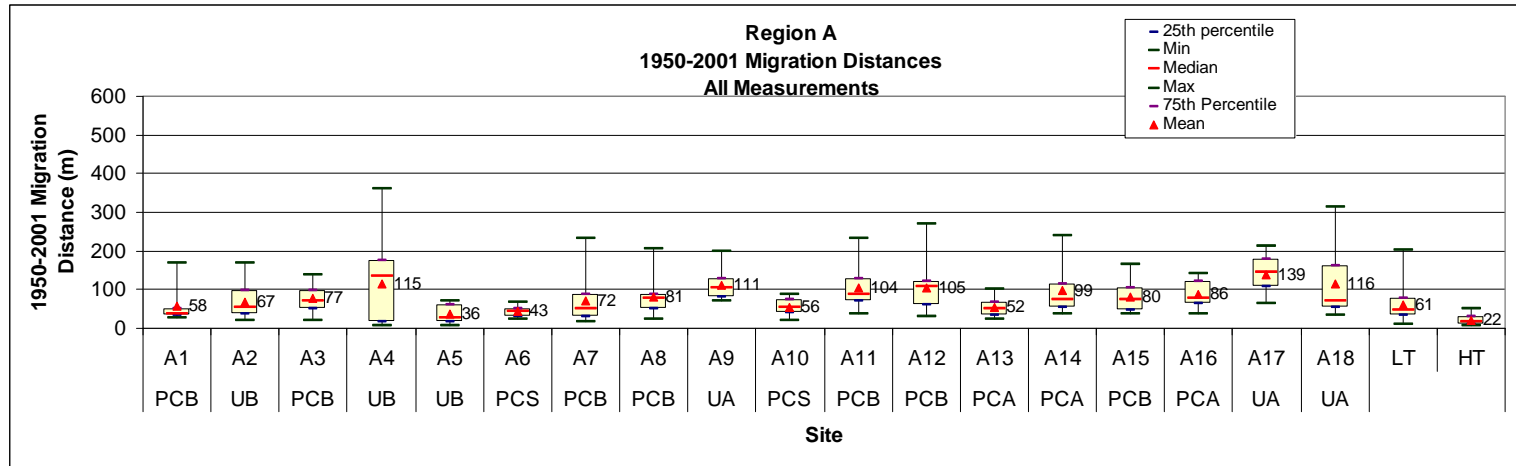

Figure C-4-2. Statistical results for migration distances measured for Region B (Clark Fork River Confluence to Big Horn River Confluence)
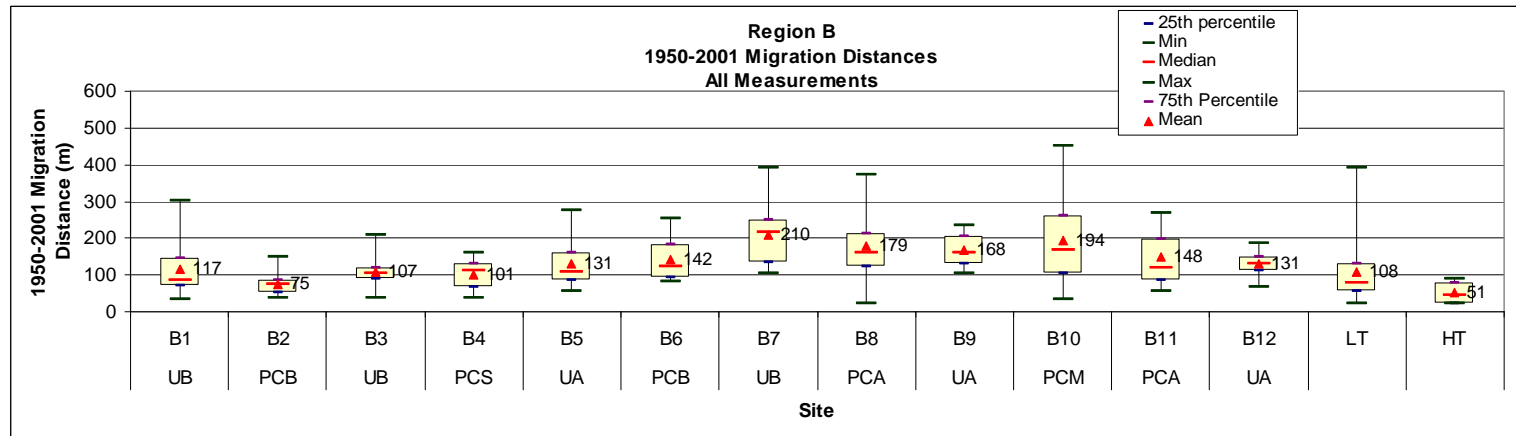
Figure C-3. Statistical results for migration distances measured for Region C (Big Horn River Confluence to Tongue River Confluence)
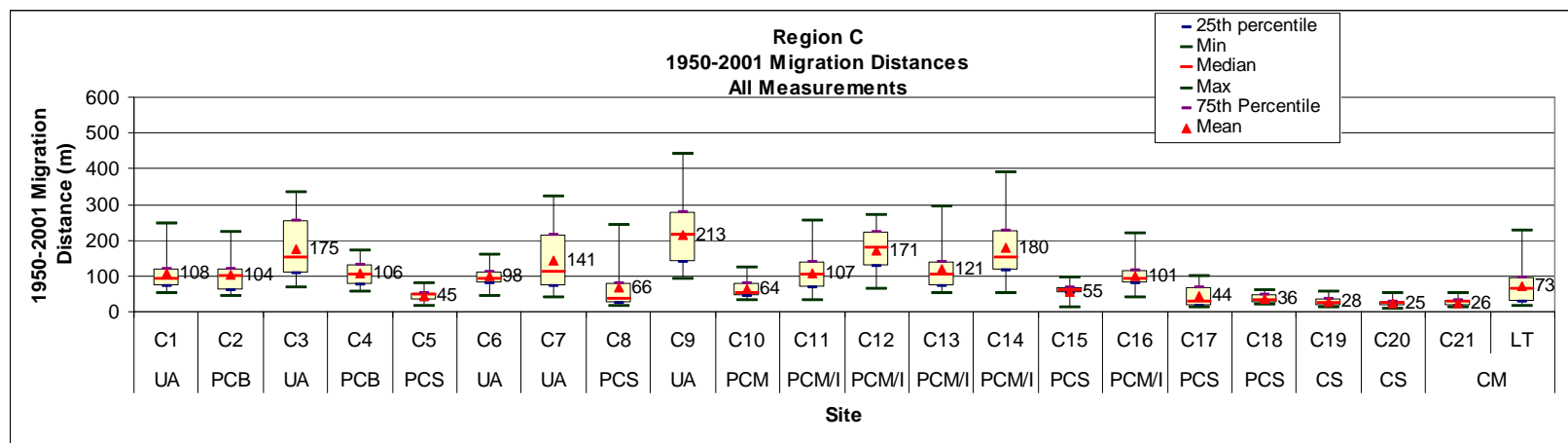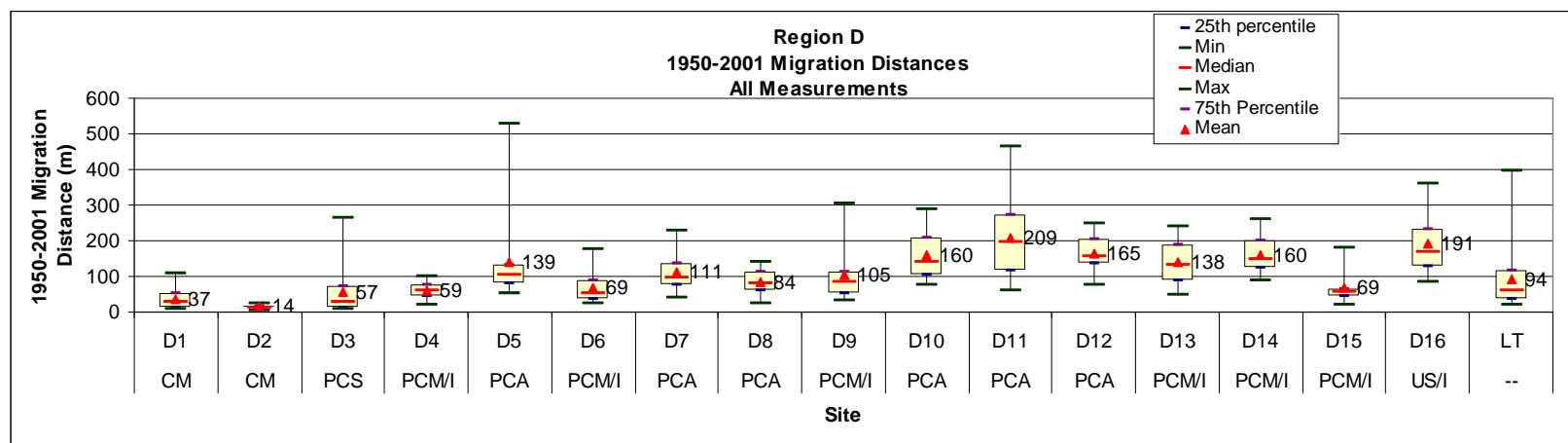

Figure C-4. Statistical results for migration distances measured for Region D (Tongue River Confluence to Missouri River Confluence)

Appendix D.   Erosion Buffer Values

Reach	Erosion Buffer (meters)	Erosion Buffer (feet)
Table D-3. Width of erosion buffer applied to each reach.		
Region A – Springdale to Clark Fork River Confluence		
A1	116	379
A2	135	442
A3	154	504
A4	229	753
A5	73	239
A6	86	281
A7	144	473
A8	163	534
A9	222	728
A10	111	365
A11	208	684
A12	209	686
A13	105	343
A14	197	648
A15	160	525
A16	172	565
A17	279	914
A18	231	759
Qt1 (A)*	61	200
Qt2 (A)*	46	151
Region B – Clark Fork River Confluence to Big Horn River Confluence		
B1	233	766
B2	149	490
B3	215	704
B4	202	663
B5	262	860
B6	283	930
B7	420	1376
B8	357	1172
B9	336	1101
B10	389	1275
B11	297	973
B12	261	858
Qt1 (B)*	108	354
Qt2 (B)*	51	167
Region C – Big Horn River Confluence to Tongue River Confluence		
C1	217	711
C2	208	684
C3	349	1146

Table D-3. Width of erosion buffer applied to each reach.		
Reach	**Erosion Buffer (meters)**	**Erosion Buffer (feet)**
C4	212	694
C5	89	292
C6	195	641
C7	282	926
C8	132	433
C9	426	1398
C10	128	420
C11	214	702
C12	342	1124
C13	242	793
C14	360	1181
C15	110	360
C16	202	663
C17	89	291
C18	72	236
C19	57	186
C20	51	166
C21	52	169
Qt1 (C)*	73	239
Region D – Tongue River Confuence to Missouri River Confluence		
D1	73	241
D2	28	92
D3	115	376
D4	118	388
D5	279	914
D6	137	451
D7	222	729
D8	167	549
D9	210	688
D10	320	1051
D11	418	1371
D12	330	1082
D13	276	906
D14	321	1052
D15	138	452
D16	381	1251
Qt1 (D)*	94	308

* Erosion Buffers for the terraces were grouped for each region due to the low number of sites with terrace boundaries in each reach.